Real Time Photon Mapping

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Abstract

Rendering is the process in which a two-dimensional image is created by a computer from a description of a three-dimensional world. From a text file of even one hundred lines a renderer can output an image that can fool the eye into believing it was an actual photograph. However, creating an interactive three-dimensional scene which can do the same is a much more difficult task. Not only does a realistic image need to be made, but one has to be created in less than a tenth of a second. Obviously the complexity of a real time rendered image will be much less than a single static image, but realistic detail is still intrinsically important. By borrowing an idea from a static rendering method called photon mapping and changing it to run in real time, the realism of interactive three-dimensional graphics will improve greatly. Furthermore, the real time calculations discussed can be performed with a single processor. The photon mapping algorithm as well as its predecessors of ray tracing and radiosity will all be covered in detail so that the conversion of photon mapping to a real time process and the advantages the algorithm provides can be well understood. Several areas where speed or detail issues exist in the real time photon mapping algorithm will then be discussed and some ideas to solve them will be presented.

1 Introduction

Rendering is the process in which a two-dimensional image is created by a computer from a description of a three-dimensional world. From a text file of even one hundred lines a renderer can output an image that can fool the eye into believing it was an actual photograph. Such images are extremely popular in movies, video games, the Internet, and many other media fields. However, no matter what the final product is used for, there is only one goal that the rendering community is focused on: creating the most realistic image as possible. So what exactly is the most realistic image possible?

This question must be answered in one of two ways depending on the type of application the image will be used for. If one needs a single still image, the most realistic image possible would be one that could be mistaken for a photograph. When the viewer has plenty of time to study an image, the more detail that is included the better the final image. Speed would not be an issue in this case; the time it took to create the image would not matter to the viewer. However, if one needed a continuous stream of images, the most realistic stream would be one that could be played in real time. Images that were so complex that loading would prevent the stream from being played at a high enough frame rate would seem choppy and unrealistic to the viewer. Thus, a medium must be chosen between image complexity and speed. Finally, if one needed the ability to allow the viewer to "walk around" in the scene in an interactive manner, the medium between detail and speed would push further toward speed. Slow speed in an interactive setting would create inaccurate response time and become increasingly annoying to the viewer. A scene that ran fast enough with little detail would be more realistic to one with more detail that ran slowly.

It seems from this description of the most realistic image possible that techniques used to create single still images could never be used to create interactive realism. However, with the recent creation of a still image rendering technique called photon mapping, interactive realism can be increased greatly. This technique, though modeled for creating a single image, has certain properties and ideas that can be directly applied to real time situations. Thus, real time photon mapping can easily implement several phenomenon in an interactive environment that were either very difficult or impossible to perform before.

In Section 2 the history of the photon mapping algorithm will be introduced, which will, in turn, introduce two of photon mapping's predecessors: ray tracing and radiosity. In Sections 2.1 and 2.2 the ray tracing and radiosity algorithms will be discussed in detail so that the reasons behind the creation of photon mapping can be well understood. In Section 3 the photon mapping algorithm for single still images will be discussed in detail using a great deal of information from Sections 2.1 and 2.2 as a background. In Section 4 the conversion of the photon mapping algorithm into a real time process will be introduced and discussed. The steps required to make the conversion will then be presented in detail. Then, several methods to make the real time photon mapping algorithm faster, more efficient, and of higher quality will be introduced. In Section 5, the performance of the real time photon mapping will be presented and several comparisons between different settings for the algorithm will be made. Finally, in Section 6, some conclusions on the ability and practicality of the real time photon mapping algorithm will be presented and some topics for future work will be suggested.

2 Previous Work

Computer graphics has been an increasingly growing field of computer science. In 1968, when much of computer graphics was simple raster calculations, Arthur

Appel thought of a new way to render objects. His idea was to trace rays from the viewer's eye, through an image plane, and into a scene to discover where objects were located in a three dimensional world [4]. However, it wasn't until Turner Whitted extended this idea into *ray tracing* in 1980 that the technique became noticed. The inclusion of both specular reflection and transmission made the algorithm both versatile and visually appealing. Unfortunately, ray tracing could not handle diffuse reflections, which is where much of real light comes from [3]. In 1984 the radiosity alogorithm was created by researchers at Japan's Fukuyama and Hiroshima Universities and the United States' Cornell University. This algorithm, borrowed from the field of radiative heat transfer, proposed to give everything ray tracing couldn't to the graphics field. Mainly, this meant that radiosity could calculate diffuse reflection [3]. In 1986, Kajiya introduced path tracing, an extension to the ray tracing algorithm that allowed it to stochastically sample for diffuse reflections. The algorithm worked well, but noise in the image was a major problem [9]. Also, in 1986 Immel, Cohen, and Greenberg developed a specular radiosity program that could simulate specular reflections. Unfortunately, the excessive time it took to render even a small number of specular surfaces was discouraging. In 1987, AT&T introduced a MIMD parallel machine that could render simple scenes using ray tracing in real time [4]. Between 1988 and 1993, several independent groups had developed bidirectional path tracing as an extension to path tracing. Bidirectional path tracing traced several rays from the light source out into the world as needed to reduce the number of samples required by simple path tracing. Although the number of samples was reduced, the speed didn't decrease because of the highly intensive calculations, and noise was still a problem [6]. Since 1988 there has been an explosion in the number of methods trying to improve either radiosity or ray tracing, including many attempts at combining the two. Many attempts have been made at creating real time ray tracing and radiosity that used parallel machines [11, 14]. However, in 1996, Henrik Wann Jensen published the first papers on *photon mapping* [9]. Photon mapping is a technique that allows the inclusion of both diffuse and specular reflections without the speed issues or noise issues that arise from radiosity and ray tracing [9].

Photon mapping uses techniques and ideas from both ray tracing and radiosity, so it is natural to first discuss those algorithms in detail. It is also important to discuss the advantages and disadvantages of each so that the reasons behind the creation of photon mapping can be fully understood. After this background information is presented, the concept of photon mapping and its algorithm will be discussed in detail.

2.1 Ray Tracing

Ray tracing is a rendering technique that is based on the idea that the only important light rays in a model are the ones that will eventually bee seen by the observer, or *eye*. In order to render an image then, one should trace a ray from the eye through a pixel in the image, and find the first surface the ray intersects. Once this intersection point is found, a new ray, called a *shadow ray*, is traced from the intersection point to the light source. If this shadow ray first hits another object before reaching the light source, then the surface is shaded at the intersection point. If not, the light source is illuminating the surface at the intersection point (Figure 1). If the surface is a *diffuse* surface, meaning neither shiny nor transparent, then the color of the pixel can be calculated immediately. If, on the other hand, the surface is *specular*, a *reflected ray* or *transmitted ray* should be generated. This ray is then recursively sent through the ray tracing algorithm to find the color seen through or reflected by the surface. This process is repeated for every pixel in the image (or several times per pixel), until a complete image is created [5].

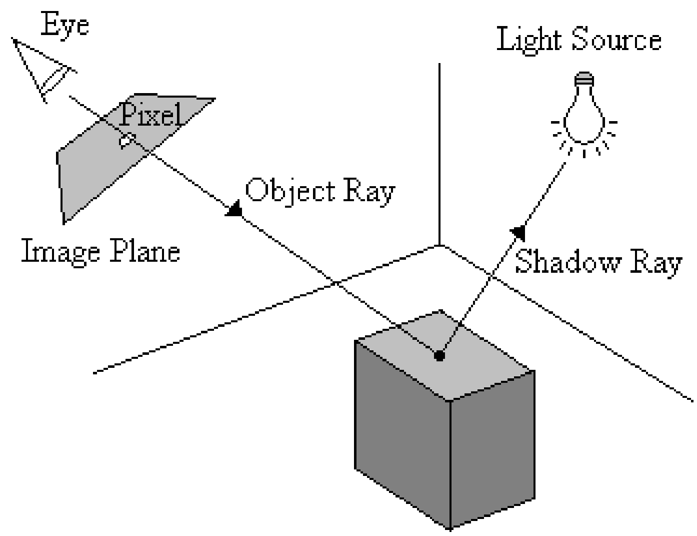


Figure 1: The ray tracing concept.

The color of each pixel is calculated by a combination of the amount of direct light seen at the intersection point of the ray and the surface, the surface color itself, and if the surface is specular, the color of the surface seen through a reflected or transmitted ray. Some of the most important equations in ray tracing are listed below [5, 13]. All vectors in the equations are unit vectors.

To calculate the color C of a diffuse surface with color S, normal $\vec{n}$, and at position $\vec{s}$ under a light with color L and position $\vec{l}$, the following is performed:

$$C = L \cdot S(\vec{n} \cdot (\vec{l} - \vec{s})) \tag{1}$$

To calculate the reflected direction $\vec{r}$ of an incoming direction $\vec{d}$ at a specular surface with normal $\vec{n}$, the following is performed:

$$\vec{r} = 2(\vec{n} \cdot \vec{d})\vec{n} - \vec{d} \tag{2}$$

To calculate the direction of a transmitted ray $\vec{t}$ of an incoming ray with direction $\vec{d}$ at a specular surface with normal $\vec{n}$ the following is performed: (*Note:* the ray is traveling from a medium with refractive index m_1 to a medium with refractive index m_2):

$$\vec{t} = \frac{m_1(\vec{d} - \vec{n})(\vec{d} \cdot \vec{n})}{m_2} - \vec{n}\sqrt{1 - \frac{m_1^2(1 - (\vec{d} \cdot \vec{n})^2\theta}{m_2^2}} \tag{3}$$

There is some disagreement between the terms "ray tracing" and "backward ray tracing". Some think "ray tracing" should be the process of tracing a ray from the light to the eye, whereas other think it should the process of tracing a ray from the eye to the light. For the rest of this paper, Glassner's perspective will be used and "ray tracing" will be defined as the rendering method suggests, tracing a ray from the eye to the light, and "backwards ray tracing" will be defined as tracing a ray from the light to the eye [5].

2.2 Radiosity

Radiosity is a rendering technique that takes into account the diffuse reflections between surfaces. Because diffuse surfaces reflect energy in the form of heat and light in all directions, it is possible for a surface that does directly "see" a light or specular surface to receive illumination. This is exactly how real light behaves. The inclusion of diffuse reflections adds reality to radiosity renderings(Figure 2) which are nearly impossible with ray tracing [3].

Radiosity is a three-pass algorithm in which the first pass is dedicated to calculating what are called *form factors* between two *patches*. Because an entire wall can be a single polygon, it may be required to be broken into several smaller polygons, or patches, so that shadows and illumination can be calculated correctly

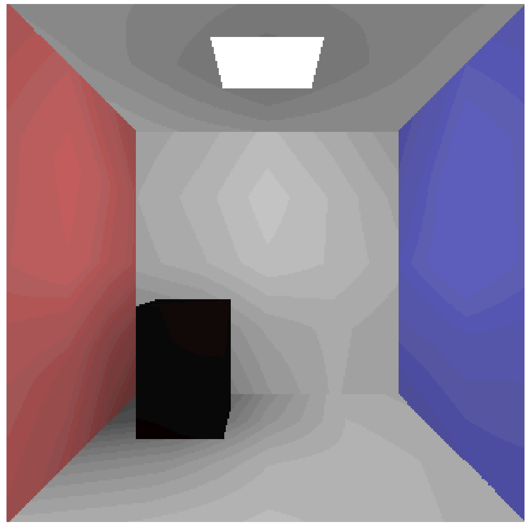


Figure 2: A simple scene rendered with radiosity.

and as realistically as possible. A surface can be divided into patches uniformly or by using algorithms such as *adaptive subdivision* to most efficiently subdivide each surface in a given scene [3]. A single form factor between two patches represents the percentage of the outgoing light from the first patch that is visible from the second patch (Figure 3). In any given scene with n patches there are $n^2 - n$ form factors (because a patch does not have a form factor with itself). Form factors can be calculated through many different methods including the hemicube, source-to-vertex, and hybridized algorithms [15].

The second pass takes all of the scene's form factors along with the light to be emitted from each light source and finds an equilibrium. An equilibrium is found when all light transfer between patches no longer changes the current illumination of any patch [3]. This may be done as one extremely large linear equation, but to save time, a process called *progressive refinement* is suggested. Progressive refinement iteratively uses the form factors to transfer energy from the lights in the scene to the patches in the scene. In other words, progressive refinement propagates the light throughout the scene one step at a time until the

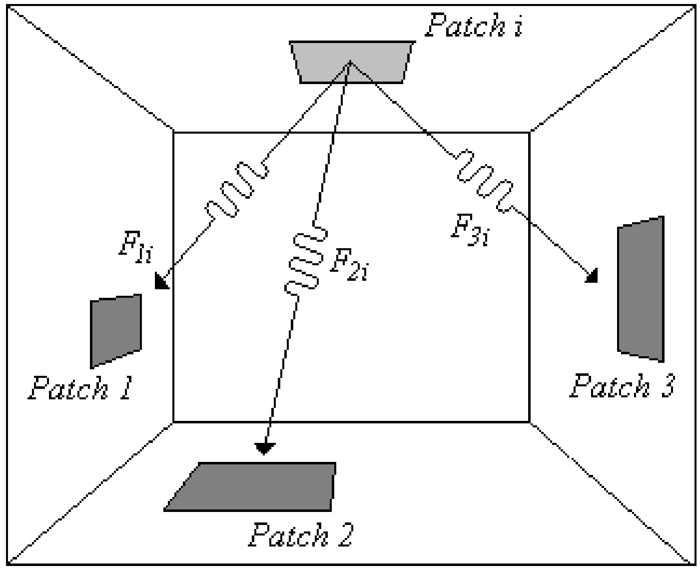


Figure 3: The concept of form factors.

equilibrium is reached. Thus, light must first be transferred from the light sources to all directly illuminated patches in the scene, then from all these patches to every indirectly illuminated patch, and so on. There may be a need for numerous iterations to reach an equilibrium in scenes where some patches only receive light through several indirect reflections [15].

Finally, after an equilibrium is reached, the scene can be rendered using Gouraud shading techniques in the third pass. API's such as OpenGL can be used by inputting the scene geometry and applying a color to each vertex that corresponds to the color calculated from the radiosity calculations. Thus, each patch in the radiosity calculations will become a separate polygon in the rendered scene [3].

Typically, adaptive subdivision as mentioned above can be used to allow for more accuracy and realism. In adaptive subdivision, each surface is divided into patches based on knowledge of which areas of the surface will be shaded similarly. This is usually done by computing a scene on a uniform subdivision, and is then refined by adding patches where the uniform patches vary in color past a predefined tolerance. By adding this step to the radiosity calculations, a more photorealistic image can be produced than with only using a uniform subdivision [3].

2.3 Shortcomings of Ray Tracing and Radiosity

Both ray tracing and radiosity can produce exceptional images as can be seen in Figures 2 and 4. However, there are many problems that keep them from creating ultimately realistic images in a reasonable amount of time. Ray tracing does not directly calculate diffuse reflections, *color bleeding*, or *caustics*, and it incorrectly calculates light passing through specular surfaces. On the other hand, radiosity cannot render specular surfaces without extreme complexity, and is extremely slow [4].

Ray tracing's first problem is that it does not include diffuse reflections. When a ray traced through a pixel hits a surface, only the surface color, position of any lights, and color of a reflected or transmitted ray (for specular surfaces only) are included in the final color calculations. The effects of other surfaces in the vicinity are not considered. This is of course not like real life and thus will not accurately depict reality. Take for example a room as shown in Figure 4 where there is a light source at the top of the room that only directly lights the floor and walls. In ray tracing the ceiling will receive no illumination, which is quite contrary to reality. Of course there have been additions to ray tracing that can help make images more realistic such as Monte Carlo integration, path tracing, and soft shadows, but these additions usually create noise and reduce speed greatly [9].

There are also several other phenomenon in real life that cannot be calculated using simple ray tracing, one of which is color bleeding. If you were to place a blue book perpendicular to a white wall you would see a slight hint of blue transferred to the wall, even if the book isn't glossy. Color bleeding requires diffuse

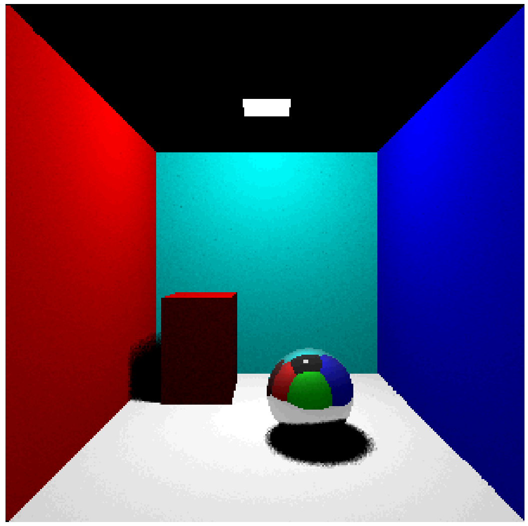


Figure 4: The unilluminated ceiling of a ray traced image.

reflections that will take into effect illumination from surfaces other than light sources. Additionally, ray tracing cannot directly implement *caustics*. Caustics are concentrated areas of light that are formed when specular surfaces focus reflected or refracted light rays in close proximity. Examples of caustics are the focused areas of light under a magnifying glass and the bright areas of light at the bottom of a pool. Although there are techniques that use backward ray tracing to implement caustics, because ray tracing itself was not designed to handle caustics, these techniques are quite complicated and time consuming [6].

Ray tracing also has problems with calculating the behavior of light reflecting off of or traveling through specular surfaces. Ray tracing does not account for light that bounces off of a reflective material and illuminates previously shaded or less illuminated areas. As shown in Figure 5, a sphere surrounded by mirrors should have three shadows around it from the illumination off the mirrors and the light source itself. However, ray tracing does not account for the illumination of the sphere on any side except for the one directly visible from the light source. The same type of problem occurs for transparent materials. Suppose a ray intersects a wall that is partially shaded by a transparent sphere. The ray tracing algorithm will create a shadow ray straight through the sphere, and because the sphere is transparent the wall will receive illumination. However, the light being emitted in the predicted direction will not illuminate that portion of the wall at all. The transparent surface will redirect illumination to areas that a ray tracer cannot predict (Figure 6).

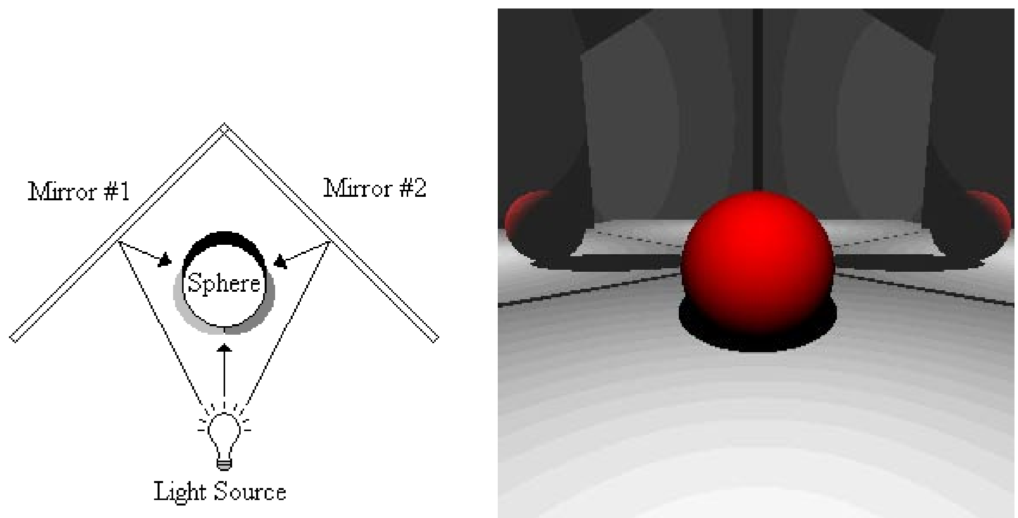


Figure 5: The incorrectly illuminated sphere surrounded by mirrors.

Radiosity, as opposed to ray tracing, was designed to allow for the diffuse to diffuse interaction between surfaces, but the cost of which is extremely expensive. Because radiosity uses the form factors as percentages of transferred illumination, radiosity can mimic both indirect illumination and color bleeding. Many of the simple images that were generated using ray tracing looked much better when generated through radiosity. Surface interaction becomes very lifelike as is visible in the soft shadows of Figure 2, and the images look amazingly like photographs. Another advantage of radiosity is its view-independent nature. Because the form factors do not take into account a camera position, the illumination of each patch can be reused if nothing moves within the scene. This is exceptionally useful in

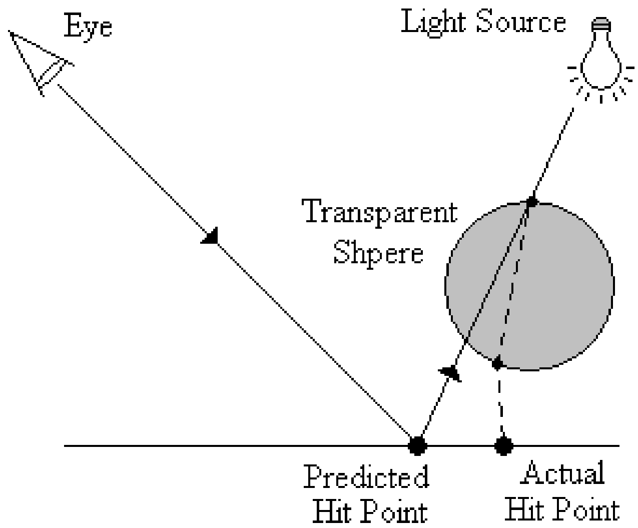


Figure 6: The incorrectly illuminated wall though a transparent sphere.

creating quickly rendered walk-throughs [3].

However, these advantages are not without pitfalls. First of all, radiosity cannot render specular surfaces. This inability is very severe in that not only can radiosity not render transparent or reflective surfaces like glass and mirrors, but it cannot render caustics at all. This shortcoming is one of the largest reasons for the creation of photon mapping as will soon be explained. Another problem is the complexity of rendering non-planar objects. Finding the form factors for spheres and tori can be exceptionally complicated using algorithms like the hemicube technique [15]. This problem can be overcome by making meshes of these objects, but this will only increase the amount of time required for rendering. Finally, radiosity is inherently slow. Creating all of the form factors may not seem like a difficult task but when we have a very complex scene with perhaps $1,000$ surfaces, 500 of which come from converting a sphere into a triangle mesh, $1,000^2$ or $1,000,000$ form factors need to be computed. Even using progressive refinement cannot keep the time required to render from being unacceptable in many situations.

There have been several attempts to combine radiosity and ray tracing techniques creating a global illumination model with indirect illumination that can still contain specular surfaces. Such examples of this are *Radiance* [12] and *POV-Ray* [16]. Unfortunately all of the speed problems still remain, and are often increased in these hybrid combinations. Obviously, a new technique that was as versatile and quick as ray tracing while still including the indirect illumination capabilities of radiosity was needed.

3 Photon Mapping

The need for an efficient yet completely illuminated rendering algorithm was answered when Henrik Wann Jensen first created the two-pass "photon mapping" algorithm in 1994 as part of his Ph.D. dissertation [9]. This algorithm achieved everything that radiosity provided but with the speed, simplicity, and surface generality of ray tracing. The premise behind his method is simple; in the first pass one simply shoots photons (*photon tracing*) from light the sources into the scene and keeps track of the energy they give to encountered surfaces. Of course there is no eye yet, but this is a two-pass algorithm; the camera will not appear until the second pass. Whenever a photon hits a diffuse surface, it is stored in a data structure called the *global photon map*. This is how diffuse reflections can be accounted for. The second pass then uses ordinary ray tracing in conjunction with the photons stored in the global photon map to capture all of the illumination types currently needed in realistic image synthesis. The result of this combination of both specular and diffuse reflections is a full global illumination model that can capture many of the surface interactions that occur in real life.

It is strange to think that in the early years of ray tracing, tracing rays from the light sources to the eye was once believed to be too complex and time consuming

[5]. Now, with the advances in computer speed and technology, this intuitive approach can be reconsidered. A closer look at the two passes of the photon mapping algorithm will now be given.

3.1 The First Pass: Creating the Global Photon Map

As previously stated, the first pass of the algorithm is to shoot photons from the light sources and then store their progress in a data structure. In order to shoot the photons we must know what type of light source we are dealing with. There are several types of light sources as shown below [9].

- *Point Light*: A single coordinate in 3-dimensional space where photons can be shot by randomly selecting any point on the unit sphere and shooting them in that direction. Jensen suggests using rejection sampling to constrain random vectors inside the unit cube to those inside the unit sphere to randomly generate point light photon emission.

- *Square Light*: This is, in general, the most popular type of light used in most rendering techniques. It looks realistic, and is easy to implement. A square light is simply a square surface that can emit photons from any point and in any direction toward the normal. There are also several techniques using square lights to allow for soft shadow generation.

- *Complex Light*: These are lights with an arbitrary shape that emit photons at different proportions in different locations. The procedure of handling these light sources will not be covered in this thesis.

Of course, if there are multiple lights in a scene, a light must be chosen before a photon can be shot. However, one cannot simply choose a random light. The probability of a light being selected must be proportional to the fraction of the light's power over the total amount of power from all lights in the scene [9].

Once the origin of the photon and its outgoing direction vector are known, the photon can finally be shot. Using much the same algorithm as traditional ray tracing, photon tracing finds the first surface that the photon would hit and proceeds to update the global photon map in one of the following ways depending on the type of surface intersected:

- If the photon hits a diffuse surface, store the photon's energy and incident direction into the global photon map.
- If the photon hits a specular surface, do nothing to the global photon map. The global photon map will only consider photons that hit diffuse surfaces.
- If the surface is partially diffuse and specular, use what is called *Russian roulette* to decide if at this particular instance the surface should be considered diffuse or specular. Russian roulette is simply the process of randomly but proportionally choosing the outcome of a probabilistic situation.

In any case, whether the photon is absorbed or reflected by the surface must now be decided. For either case Russian roulette is once again used with the surfaces reflectivity property to see if the photon should be absorbed or reflected. If the photon is absorbed, this particular photon's life is ended here. If the photon is reflected (or transmitted) the reflected ray must be calculated the process repeated as if the photon started from the intersection point. Diffuse and specular surfaces do not reflect photons in the same way, and these differences must be accounted for. While specular surfaces can be assumed to reflect perfectly using Equation (2), diffuse surfaces can reflect in any direction. This direction however is proportional to the cosine of the angle between the perfectly reflected direction and the actual reflected direction. To create the random reflection direction two random variables, ξ_1, $\xi_2 \in [0, 1]$ are needed. The reflected direction $\vec{r}$ is then given by [9]:

$$\vec{r} = (\theta, \phi) = (\cos^{-1}(\sqrt{\xi_1}), 2\pi\xi_2) \tag{4}$$

Once a predefined number of photons have been scattered throughout the scene, the photons must be sorted in a manner in which they can be easily retrieved later. For reasons that will become obvious in the next section, Jensen suggests using a k-d tree data structure to store the photons [9].

3.2 The Second Pass: Generating the Image

The second pass of the algorithm creates an image in much the same fashion as ray tracing. It traces rays from the camera point through each of the pixels and finds the first surface the ray encounters. The color given to the pixel depends on the type of surface at the intersection point. If the surface is specular, a new reflected or transmitted ray is generated and traced using Equations (2) or (3). On the other hand, if the surface is diffuse, several sample reflected rays using Equation (4) are created. For every reflected ray that hits another diffuse surface, a *radiance estimate* at the intersection point is taken.

The radiance estimate finds the m closest photons in the photon map to the inputted intersection point within some predefined distance (Figure 7). This is the reason a k-d tree is suggested for the photon map. A k-d tree can easily traverse a list of coordinates in three dimensions until the closest photon is found. This can be done in $O(\log_2 n)$ time for n total photons on average. Finding the next $m - 1$ nearest neighbors is from this point a trivial task [10]. Along with the k-d tree's lack of memory overhead, it is obvious why it is a great candidate for the photon map's data structure. The radiance estimate is then found by totaling the illumination of the m nearest photons and dividing by the area in which they were found. This area is the area of the circle with a radius of distance from the intersection point to the furthest of the m nearest neighbors [9].

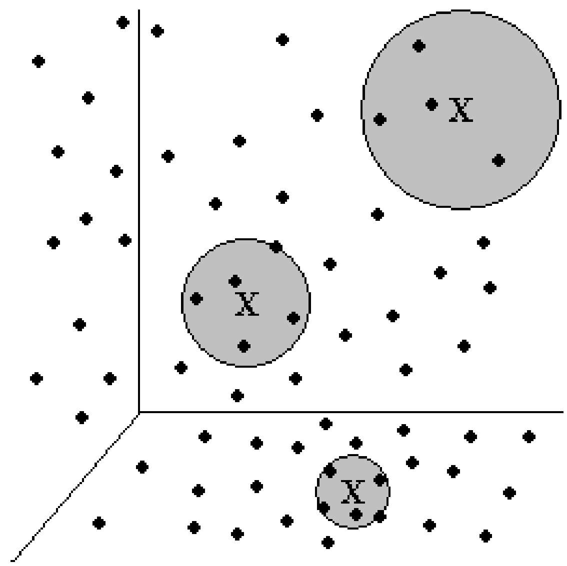


Figure 7: How the radiance estimates are visualized.

Once all of the sample radiance estimates are found, they are averaged together. This estimates the indirect illumination that the intersection point receives. This can then be combined with the direct illumination from the light sources and any specular properties to create an image using a global illumination model (Figure 8).

3.3 Color Bleeding and Photon Mapping

Because the radiance estimates of the photon mapping algorithm account for diffuse reflections, it is possible to render color bleeding. Color bleeding can be achieved simply by changing the color of the photons as they are reflected throughout the scene. For example, if a white photon is reflected off of a blue wall, the photon would now be blue, and the next time it hits a diffuse surface it should be stored in the photon map as being blue. Unfortunately, Jensen fears that in order

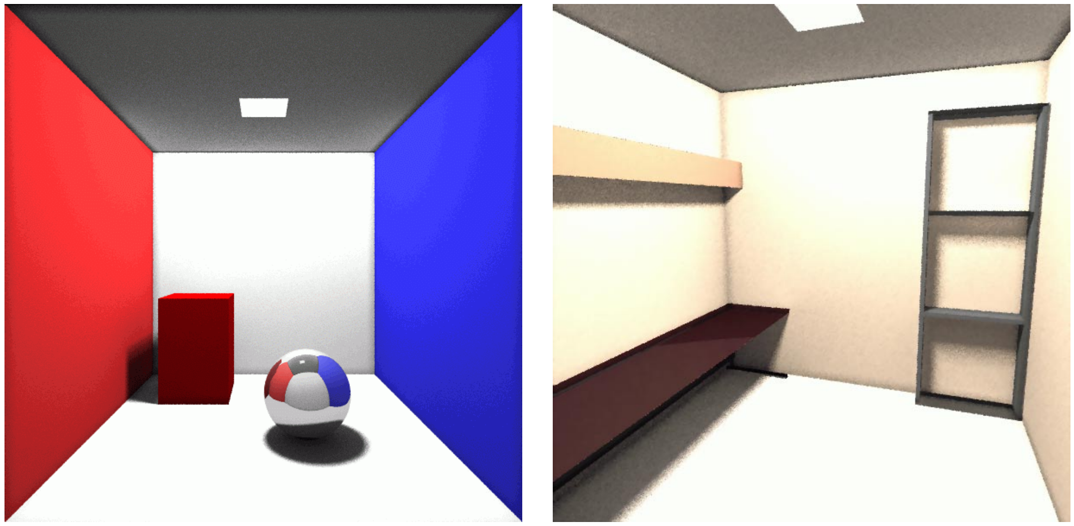


Figure 8: Two photon mapped images.

to render color bleeding without what he calls "blotchy" effects would take more than millions of photons [9]. However, this is not the case as can be seen from Christensen's work. Several of his images using $400,000$ photons can be seen to exhibit quite realistic color bleeding [2].

3.4 Caustics and Photon Mapping

One major advantage of photon mapping is the ability to create wonderful caustics. Jensen suggests keeping a second photon map called the caustics map to capture all photons that have been reflected by or transmitted through a specular surface at least once before hitting a diffuse surface. Once a photon hits a diffuse surface its life should be ended. The caustics map however needs to be constructed carefully to make sure that photons are not repeated in the global photon map. Once this is added to the photon mapping algorithm, the final pixel value is a combination of the direct, indirect, specular, and caustic illuminations [9].

4 Real Time Photon Mapping

In the graphics community it seems that as soon as an algorithm becomes established, someone tries to make it faster. For years, the proponents of ray tracing and radiosity discovered new ways to make each algorithm faster, more efficient, and more realistic. The epitome of these improvements would be to have the algorithms execute in real time. Radiosity had an advantage over ray tracing in that it could easily render interactive walk-throughs. However, these walk-throughs were not interactive. To accomplish real time interaction, one must account for objects and light sources that move. Radiosity's walk-throughs do not inherently allow this; however, it seems easier to apply real time to radiosity because the radiosity calculations are independent of the rendering technique. We can find the form factors and the correct illuminations without having to worry about how to render the scene. This allows radiosity to easily be rendered using OpenGL or even ray tracing as hybrid techniques have shown. Ray tracing does not have this advantage; it is the rendering technique itself and thus cannot be changed without extensive effort. However, both ray tracing's strong connection to the rendering process and radiosity's slow speed did not keep them from being used to create real time algorithms. There are several examples of real time ray tracing and real time radiosity systems available, many of which require parallel machines to execute [11, 14].

Photon mapping has the benefit of once again having both ray tracing's and radiosity's advantages while possessing none of their flaws. As with radiosity, photon mapping is independent of the rendering process. Though most examples of photon mapping use standard ray tracing to render, it is feasible to use other methods. And while radiosity calculations become the bulk of the time complexity, photon mapping itself takes a relatively small percentage of the rendering time.

It seems obvious that photon mapping can be transferred to the area of real time interactive rendering. Furthermore, the speed of photon mapping is so fast that it is also possible to perform real time rendering on a single processor machine.

4.1 The Concept

The concept of real time photon mapping is simple. Instead of shooting hundreds of thousands or millions of photons once to render a scene, merely shoot tens or hundreds of photons per frame. By limiting the number of photons shot, one can minimize the per frame shooting time, making real time photon mapping not only possible but practical. However, since tens or hundreds of photons will not be adaquate to simulate the indirect illumination of a scene, the last several frames of photons can be stored and reused. Once photons become old enough, they can be overwritten by a newly shot frame of photons, thus keeping only the newest several frames of photons maintained. Then, by using normal polygon-based rendering methods such as OpenGL and a radiance estimate at each vertex of each polygon, diffuse reflections and even color bleeding can be simulated. The process of real time photon mapping can be broken down into three main stages which can be seen through the algorithm outlined in Figure 9. These three stages: shooting the photons, balancing the k-d tree, and applying the radiance estimate are dicussed in detail in the following sections.

4.1.1 Stage 1: Shooting the Photons

There are three major issues in the first stage, the first two of which are choosing a total number of photons and deciding how many photons to shoot per frame. The third concerns choosing the distribution from which to shoot these photons.

Choosing how many total photons to shoot and how many photons to shoot

```
index := 1               // the index of the first photon to shoot per frame
per_frame := 100         // the number of photons to shoot per frame
total := 2000            // the total number of photons to store
while true do
   begin
      // Stage 1: Shooting the photons: Section 4.1.1
      shootPhotons(index, per_frame)

      // Stage 2: Balancing the k-d tree: Section 4.1.2
      balance()

      // Stage 3: Rendering the image: Section 4.1.3
      for all polygons do
         begin
            // find radiance estimate at each vertex
            // render polygon with illumination at vertices
         end

      index := (index + per_frame) modulo total
   end
```

Figure 9: The proposed real time photon mapping algorithm

per frame is not a trivial task. Let `total` and `per_frame` represent these numbers respectively. Both `total` and `per_frame` should be chosen carefully for several reasons. Increasing `per_frame` will increase the number of photons that are shot every frame, so shooting too many `per_frame` photons will obviously result in slow processing times. Increasing `total` too much will also slow processing times because more photon hits must be balanced and searched through for the radiance estimates. Selecting too few `per_frame` or `total` photons will obviously decrease the frame quality as the original photon mapping algorithm has shown [9]. However, by choosing a good balance between `total` and `per_frame`, one can create a scene with reasonable results for any machine speed. Sections 5.1 and 5.3 discuss further how changing these numbers will effect the output.

Once the number of photons to use are known, one can simply shoot `per_frame` photons into the scene before each frame. However, it would be beneficial to save and reuse the last frame's photons because they are still relevant to current conditions. Very small changes occur between frames when the frames are being generated fast enough, so photons shot even a second ago can still give a proper representation of the current scene. It is because of this that the `total` photons are chosen. This number represents the maximum number of photons at any time in the scene. Once the scene is filled with `total` photons, the oldest `per_frame` photons are now irrelevant and can be thrown away and replaced with a newly shot set of `per_frame` photons. Each frame then has at any given time a total of `total` most recent photons. This process will be covered in more detail in Section 4.1.2.

There is one more option that must be decided and that is the distribution used to shoot the photons. A distribution in this sense is pattern in which the photons are dispersed throughout the scene. There are three major options:

- Shoot every photon randomly into the scene.
- Shoot each `per_frame` set of photons with the same distribution.
- Shoot each `total` set of photons with the same distribution.

By shooting every photon randomly into the scene one can be assured that over time, each possible path for a photon to take will be accounted for. Random shooting is also very easy to implement. However, this will also result in some fluctuation between frames because each frame overwrites its last `per_frame` photons with ones shot in a completely different manner. This fluctuation can be lowered by choosing an appropriate number of `total` photons and `per_frame` photons, but changing these numbers can only effect the fluctuation slightly.

Shooting each frame of photons with the same distribution is the exact opposite as random shooting. Every `per_frame` photons are shot with the same pattern as the last `per_frame` photons. This method will keep any fluctuation between frames to a minimum; however, this method may also keep areas of a scene from being illuminated. Because the number of different paths the photons can travel is limited to `per_frame` directions, the coverage of the photons is low. This results in some sections of the scene being highly illuminated, and some being poorly illuminated.

The last case is the suggested option: a distribution is chosen for the `total` number of photons. This means that after `total` / `per_frame` frames have passed, the distribution will be repeated. This allows for a good medium between low fluctuation and high coverage.

4.1.2 Stage 2: Balancing the K-D Tree

Balancing the k-d tree, as covered in Section 3.2, is necessary for the radiance estimate calculations. By using a k-d tree to store the photons, a minimum amount of memory is used, while allowing the search of the nearest m photons to an inputted hit point to be performed in $O(\log_2(\texttt{total}))$ time. A k-d tree is balanced by choosing a median photon positioned along one of the coordinate axes and then dividing the rest of the photons into two halves, the ones below the median and the ones above it. This process is repeated by choosing the next axis and then recursively balancing each of the halves. Figure 10 shows how a k-d tree divides a set of two dimensional data.

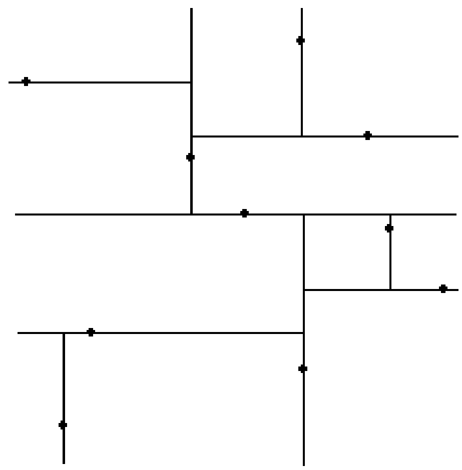


Figure 10: How a k-d tree divides a set of two dimensional data.

Balancing of the k-d tree in the photorealistic photon mapping algorithm was dependent on the maximum number of photons shot. In the proposed real time photon mapping algorithm it will be dependent on the value of `total` photons. It is suggested here that all of the photons be shot for the first frame. In this way the illumination of the first frames will not be lacking. Now, for every frame there will be on the order of `total` photons in the k-d tree that will need to be balanced. Each frame the corresponding `per_frame` photons are simply overwritten with new data.

The first problem that arises is how to handle diffusely reflected or specularly reflected or transmitted photons. Because a photon may be reflected a different number of times each time it is shot (this is due to either being randomly absorbed or being reflected by a different object), a way to handle any number of reflections must be created. This can be done in the following way. If a maximum reflection level `max_level` is chosen (three has been seen to be sufficient for real time rendering) then an array of `max_level` · `total` photon hit locations is needed. This array of photon hits, called `photons[ ]`, is conceptually broken into `max_level` contiguous sections, with each section representing the first, second, etc. hits of each of the `total` photons. The first time a photon with index `i` hits a surface its information is put into position `i` in the array. The second time it hits a surface its information is put into position (`i` + `total`) and so on (Figure 11). If a photon hits a specular surface, the corresponding position in the array should be marked as unused. The same should be done for all remaining positions if the photon is absorbed through Russian roulette as described in Section 3.1.

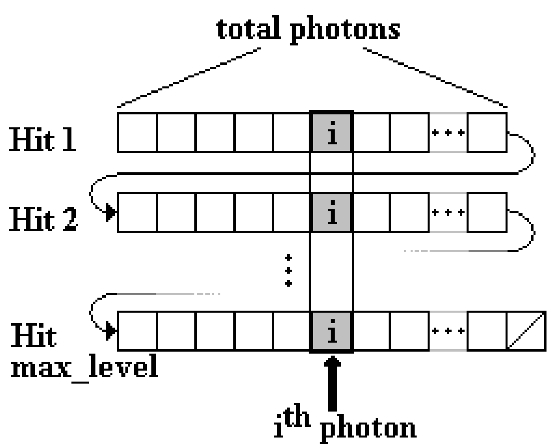


Figure 11: The `photons[ ]` array with length `total` · `max_level`.

Another problem is how to keep track of the photons in the k-d tree. Once the k-d tree is balanced for each frame, the photons are no longer in the same order they were in. This will make removing the oldest `per_frame` photons and reshooting them extremely difficult. To overcome this, an array of integer indices, called `photon_location[ ]`, can be created to show the position in the photon array that a photon is currently located. Thus, when the balancing is performed, the `photon_location[ ]` array is updated along with the `photons[ ]` array. Then removing and reshooting the oldest `per_frame` photons (starting with photon `i`) consists of simply updating the photons stored at `photons[photon_location[i, i+per_frame]]` (Figure 12).

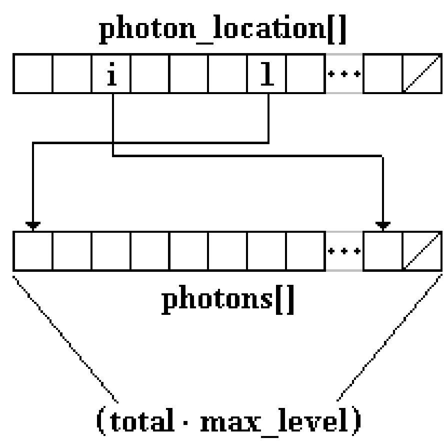


Figure 12: The `photon_location[ ]` array and its relation to the `photons[ ]` array.

4.1.3 Stage 3: Applying the Radiance Estimate

Now that the photons have been shot and the k-d tree has been balanced, we now need to use that information to render the scene. By using the same radiance estimate as used by the photorealistic photon mapping algorithm (Section 3.2), we can find the diffuse illumination at each vertex in the scene. This will give us a new type of realism in real time interactive programs that previously did not exist.

The only real problem in this stage is choosing the number of photons to collect in the radiance estimate. If we choose too many, then we will suffer slowdown in this stage. If there are too few then we will have inaccurate estimation and dimmer illumination [9].

4.2 Changes to the Photon Map

To accommodate for the real time photon mapping algorithm, we have to change the photorealistic photon mapping algorithm slightly. While these changes may modify the functionality, the concept behind the methods will not be altered. The changes that must be made include additions to the `Photon` structure and of the `photon_location[ ]` array, and changes to the functions that shoot all of the photons, shoot a single photon, store a photon hit in the k-d tree, scale the stored photon power, balance the k-d tree, and locate the photons for the radiance estimates.

4.2.1 Additions to the Photon Mapping Algorithm

Because knowing which photons are not currently being used in the photon map is essential, the first change to be made is in the photon itself. To allow for photons to be skipped in the radiance estimate if they occurred at a specular surface or were absorbed due to Russian roulette, we need to add a single bit flag called `used`. If the photon is "live" and should be considered in the radiance estimate we set the `used` flag to true. If not, we set the `used` flag to false. The new photon structure should look like Figure 13.

Next, in order to remember which photon is which after the k-d tree is balanced an integer array should be added to the photon map. This array is the

typedef struct *Photon*
    begin
        float *pos*[3];
        short *plane*;
        unsigned char *theta*, *phi*;
        float *power*[3];
        bool *used*;
    end *Photon*;

Figure 13: The new `Photon` structure.

for $i := 1$ **to** $total \cdot max\_level$ **do**
    begin
        $photon\_location[i] := i$
    end

Figure 14: Initializing the `photon_location[ ]` array.

`photon_location[ ]` array and will contain the index in the photon array that this photon is located at. This way, to know where `photons[1]` is located after balancing, one looks at `photons[photon_location[1]]`. This array is initialized in Figure 14.

4.2.2 Changing the Photon Shooting Functions

To allow for shooting only a select few photons into the scene every frame, a change must be made to whatever function previously shot all of the photons (this function will be referred to as `shootPhotons()`). Instead of shooting all of the photons into the scene until the max number of storable photons is reached, one must now be able to shoot a `per_frame` number of specific photons (or the `total` number of photons if it is the first frame). This can be done by including both

```
shootPhotons(int num_photons, int index)
  begin
    level := 0
    photon_ray := emitPhoton() // returns a ray from the light
    light_power := getLightPower() // returns the light's power
    for i := index to num_photons do
      begin
        shootOnePhoton(i, level, photon_ray, light_power) // Figure 16
      end
    scalePhotonPower(index, num_photons); // Figure 18
  end
```

Figure 15: The function to shoot the `per_frame` photons.

an `int num_photons` and an `int index` as parameters to the `shootPhotons()` function. This way `per_frame` photons starting from a desired `index` can be shot. When used in combination with the photon location array, photons can be shot and reshot. The basic layout of the function to shoot the photons from a single light source can be seen in Figure 15.

The `shootOnePhoton()` function as mentioned in Figure 15 must now be able to shoot a single photon with the real time changes. Previously this function is where the first surface the photon hit would be found. Russian roulette would then be used to see if the photon was diffusely reflected, specularly reflected, specularly transmitted, or absorbed. Only if the photon hit a diffuse surface would the photon be stored, but now we must store the photon in every case so that previous data can be overwritten. The new function for shooting a single photon can be seen in Figure 16.

```
shootOnePhoton(int index, int level, Ray p_ray, Vector power)
    begin
        if level ≥ max_level then return
        p_dir := p_ray.direction // the Vector direction of the ray
        if (p_ray intersects an object at hit_point)
            then
                if (object is specular)
                    then
                        // find reflected or transmitted ray r_ray
                        store(index + (level · total), power, hit_point, p_dir, false)
                        shootOnePhoton(index + total, level + 1, r_ray, power)
                    endif
                else if (surface is diffuse and absorbed)
                    then
                        store(index + (level · total), power, hit_point, p_dir, true)
                        for i := level + 1 to max_level do
                            begin
                                store(index + (i · total), power, hit_point, p_dir, false)
                            end
                    endif
                else if (surface is diffuse and reflected)
                    then
                        // find diffusely reflected ray r_dir
                        store(index + (level · total), power, hit_point, p_dir, true)
                        shootOnePhoton(index + total, level + 1, r_ray, power)
                    endif
            endif
    end
```

Figure 16: The function to shoot a single photon.

```
store(const int index, Vector power[3],
      Vector pos[3], Vector dir[3], bool used)
   begin
      Photon node := photons[photon_location[index]]
      node.used  := used
      node.pos   := pos
      node.power := power
      node.dir   := dir
      Update bounding box for k-d tree if needed.
   end
```

Figure 17: The function to store a photon hit in the `photons[ ]` array.

4.2.3 Changing the K-D Tree Functions

The `store()` function is used to record the position of a photon hit into the k-d tree. As can be seen in Figure 16, changes to this function as suggested by Jensen must be made [9]. This is because now a specific photon must be stored, and it may also be the case that the photon should be flagged as "not used." These changes can be completed by adding a few more parameters: a `bool used` and an `int index`. If `used` is true, then the photon's `used` flag should also be set to true. If false, the `used` flag should be set to false. This allows us to overwrite photons so that if they were used in the previous frame, they will not be used in the current frame or vice versa. The `index` is included to point to the correct photon. This is the original index of the photon however, so the `photon_location[ ]` array must be used. The bounding box used for the k-d tree does not need any changes as one might suspect. Because the bounding box is only used to find a suitable median for the k-d tree an appropriate amount of photons should always have the same bounding box frame after frame. The revised photon storing function can be seen in Figure 17.

$$
\begin{array}{l}
\mathit{scalePhotonPower}(\textbf{const float } \mathit{scale}, \textbf{ const int } \mathit{num\_photons}, \\
\qquad\qquad\qquad \textbf{const int } \mathit{index}) \\
\quad \textbf{begin} \\
\qquad \textbf{for } j := 0 \textbf{ to } \mathit{max\_level} \textbf{ do} \\
\qquad\quad \textbf{begin} \\
\qquad\qquad \textbf{for } i := 0 \textbf{ to } \mathit{num\_photons} \textbf{ do} \\
\qquad\qquad\quad \textbf{begin} \\
\qquad\qquad\qquad \mathit{loc} := i + \mathit{index} + (j \cdot \mathit{total}) \\
\qquad\qquad\qquad \textbf{Photon } \mathit{node} := \mathit{photons}[\mathit{photon\_location}[\mathit{loc}]] \\
\qquad\qquad\qquad \mathit{node.power}[0] := \mathit{node.power}[0] \cdot \mathit{scale} \\
\qquad\qquad\qquad \mathit{node.power}[1] := \mathit{node.power}[1] \cdot \mathit{scale} \\
\qquad\qquad\qquad \mathit{node.power}[2] := \mathit{node.power}[2] \cdot \mathit{scale} \\
\qquad\qquad\quad \textbf{end} \\
\qquad\quad \textbf{end} \\
\quad \textbf{end}
\end{array}
$$

Figure 18: The function to scale the newest `per_frame` photons' power.

When the photons in the `photons[ ]` array are stored, they are initially given the same power as the light source they were emitted from. However, each photon only has a fraction of this power, so each of the newly shot `per_frame` photons' power must be scaled. In order to scale the photon power of the correct photons we must also change the `scalePhotonPower()` function as proposed by Jensen [9]. Previously, in the photorealistic photon mapping algorithm, all of the photons were scaled at once without regard to their current locations in the k-d tree. This is no longer the case. Thus, the changes required are to use the `photon_location[ ]` array to scale the correct `per_frame` photons. This keeps photons from being scaled more than once, and keeps newly reshot photons from not getting scaled at all. The changes to the scaling function can be seen in Figure 18.

During the k-d tree balancing in the `balance()` function, a photon's index will be changed in order to create the balanced tree. This requires a change to the original code so that the position of each photon can be kept. This way shooting photons 1 through 100 will still shoot photons 1 though 100 after the balancing. This can be done by updating the `photon_location[ ]` array while the balancing is being performed. The changes to the balancing function are quite simple so they will not be shown. The needed changes must make sure to swap the values in the `photon_location[ ]` array every time the photons in the `photons[ ]` array are swapped.

4.2.4 Changing the Radiance Estimate Functions

Finally, we must make changes to the radiance estimate to ignore any photons that have their `used` flags set to false. Thus, a photon with its `used` flag set to false will not be a nearest photon to the point in question. This may add time to the duration of the radiance estimate but it will be negligible. To make these changes simply ignore any photons whose `used` value is set to false (These changes are simple as well so they will not be shown).

4.3 Using Subdivision for More Detail

In many cases the original scene geometry may not provide enough detail in the final rendering. In this case it may be advantageous to use an algorithm similar to adaptive subdivision. By correctly choosing locations to divide a surface into smaller more precise patches, we could increase the detail of our scene. Unfortunately adaptive subdivision uses a “trial” version of the scene to discover which areas need to be subdivided. Because of the lack of time for a real time system to perform a “trial” version, a uniform subdivision may be all that can be done.

4.4 Speed Issues

There are several key places in the real time photon mapping algorithm that may affect rendering speed. Because the algorithm is real time, all speed issues are the most important issues even above realism and quality and as such should be discussed. Those areas that have non-trivial solutions will be discussed in detail later in this section with their possible solutions. The following are the areas in question:

Shooting the Photons: The number of photons that will be shot per frame is of major importance in how fast a frame can be rendered. This `per_frame` number should be chosen as the number that can most accurately illuminate the scene while still being fast enough to render enough frames per second. Some guidelines for picking this value are given in Table 1.

Finding Hit Points: The time required to find the surface a photon hits is directly proportional to the number of surfaces in the scene. Since we cannot simply require scenes to have few surfaces, we must use other techniques to limit the surfaces checked for intersection. More on this topic will be discussed in Section 4.4.1.

Balancing the K-D Tree: The total number of photons used is obviously the major factor in how long balancing the k-d tree takes. As more photons are included, the time for balancing will grow accordingly. Although $O(n \log_2 n)$ is quite fast for the balancing, it may be necessary and possible to speed it up. A solution to this problem has not yet been found and the problem itself is a major topic for future work.

The Radiance Estimate: The speed the radiance estimate takes is based on how many photons are desired. A greater number will give better results (to an extent) while a smaller number will be faster. However, because finding more neighbors after the first neighbor is found is trivial, the time spent for a single radiance estimate cannot be changed much.

Selecting Vertices to Render: Although the time spent finding a single radiance estimate cannot be changed much, if there are many vertices in the scene, the total time spent doing radiance estimates may become large. Thus we must use techniques that can limit the number of radiance estimates performed to only ones that effect what is displayed. More on this topic will be discussed in Section 4.4.2.

4.4.1 Checking Fewer Surfaces for Intersection

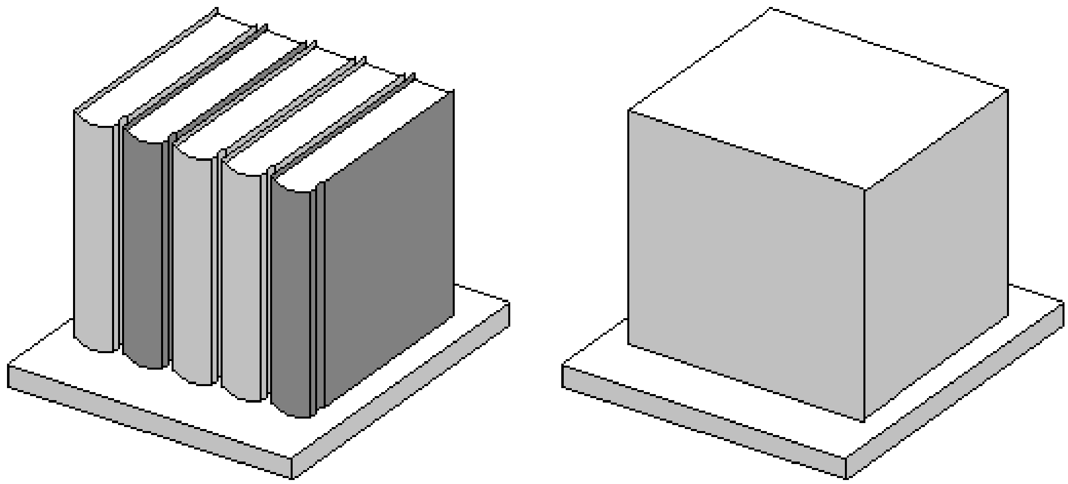
The issue of finding the surface that a photon hits first is one that has been studied extensively for ray tracing. Because photons go through the same process that rays go through, the techniques discovered for ray tracing can be directly applied for photon mapping in general. Some of these techniques are listed below.

Bounding Volume Hierarchies: By placing a bounding volume such as a sphere or box around a set of objects, testing to see if a photon hits one of the objects within becomes much simpler. If this is done for many or all of the objects in a scene, finding the intersection of a surface and the photon becomes a hierarchical process of searching first the bounding volumes and then the objects inside. These objects may be the surfaces themselves or other bounding volumes [6].

Space Subdivision: Breaking up the scene into a set of three-dimensional *cells* can provide a way to speed up intersection times as well. Each cell will have a list of all the objects that are inside it. When a photon reaches a cell, it will check with all the objects in the cell's list to see if there is an intersection, if there is none, the photon is propagated to the next cell. The creation of the cells can be uniform or adaptive, and a surface may lie in any number of cells simultaneously [6].

Directional Subdivision: By subdividing the space into regions based on the distribution of the photons, it is possible to receive better results than space subdivision. This algorithm is nearly the same as space subdivision except that the cells are created not as boxes of the environment but as pyramid shaped volumes that represent similar directions a photon can be shot [6].

These algorithms all work well, but photon mapping has a property that can be exploited to help reduce the number of surfaces checked further. An advantage of the photon map is that it is separate and independent of the geometry of the scene. Using this attribute we can perform a single *scene simplification* and still get good results. Suppose the rendering of a set of books in real time (Figure 19). The photon map itself doesn't need to know all of the geometry of the books including the curved bindings and covers. It simply needs to know the general perimeter of the books in which photons should be stored on. Since the radiance estimates will depend on proximity instead of exact location, the books can be replaced by a single box and still be rendered with high quality (Figure 19). However, this requires two versions of the scene: one to be rendered and one to use for photon shooting. If desired, one can input each scene twice from two different source files. This scene simplification can reduce the number of surfaces greatly in a scene and make the photon shooting stage much quicker. See Section 5 for some results.



(a) (b)

Figure 19: An example of scene simplification from (a) an original model to (b) a reduced model.

4.4.2 Fewer Radiance Estimates

For the same reasons that the number of surfaces checked for intersection should be reduced, the number of vertices that perform a radiance estimate should also be reduced. Because each vertex in the scene is the location of a radiance estimate, the more vertices that can be discovered to be uneventful, the more time can be saved. Of course, discovering if a vertex will affect the scene is more than simply checking if the vertex will be seen. If any portion of the polygon can be seen, then all of its vertices are eventful, and thus a radiance estimate should be performed. There are several methods for performing this needed *vertex removal*, some of which are outlined below:

Hidden-Surface Removal If at any time a polygon cannot be seen at all, all of its vertices should be withheld from performing radiance estimates. This includes any polygons that are not in the viewing frustrum or are totally obscured by other polygons. A good algorithm used to perform this is the z-buffer algorithm [1].

Back Face Culling Approximately one forth of the polygons in any given frame are facing away from the camera. As long as there are no "thin" objects in the scene, these polygons can also be ignored as well as their vertices. If the angle between the camera ray and the surface normal is less than ninety degrees, the surface can be ignored for this frame[1].

There is also another way of decreasing the number of radiance estimates required to render a frame. By realizing that many polygons share vertices, we can perform only one radiance estimate for the vertex and share the information between the polygons. This can be done by connecting each of a polygon's vertices with a *corner* (Figure 20). Instead of finding the illumination at each vertex, the illumination is found at each corner. Then, each vertex is rendered with the illumination found at its corresponding corner. Some results of vertex cornering and back face culling can be seen in Section 5.

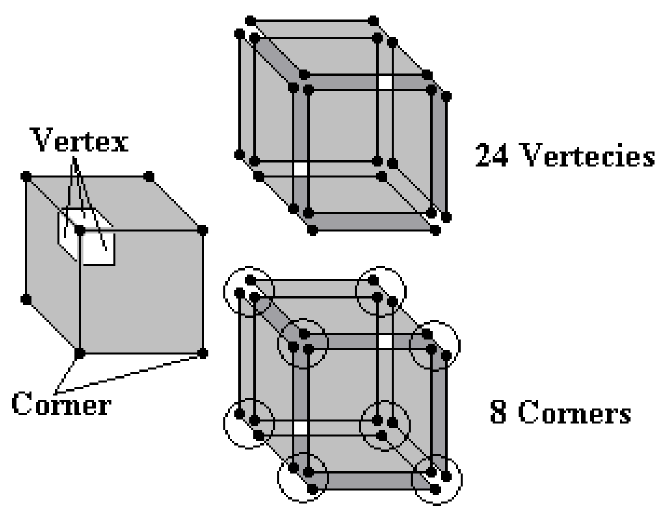


Figure 20: Reducing the number of radiance estimates using corners.

5 Results

The proposed real time photon mapping algorithm is of little practicality if it cannot render frames fast enough. On the other hand, if the visual results do not show the phenomena expected, the algorithm will be superfluous. Because of this, several tests need to be performed. These tests include changing the important parameters of the algorithm to generate performance statistics, determine speedup capabilities, and verify the visual quality of the results. Several phenomena that can be performed using real time photon mapping will also be presented and visually verified.

5.1 Performance

Performance statistics are probably the most important statistics for any real time algorithm because they prove that the algorithm can be executed fast enough to be performed in real time and fast enough not to be visually distracting. These statistics also show how changing the values of different variables effect the speed in which frames can be generated. All of the statistics in this section were performed on a 866MHz Pentium III machine. Furthermore, each of the total per frame rendering times are broken down into the algorithm's three stages: shooting the photons, balancing the k-d tree, and calculating the radiance estimates.

Figure 21 shows how changing the value for `per_frame` effects the per frame rendering times. Each test scene consisted of 16 surfaces, $2,000$ `total` photons, a `max_level` of 3, 100 photons in each radiance estimate, and a 512 by 512 pixel output window. The first thing one should notice is that even as the number of `per_frame` photons increases, the total rendering time is less than 0.06 seconds. Although a scene should be rendered at a rate of roughly one frame every 0.05 seconds to seem fluid to the human eye, these numbers are extremely optimistic.

The second point to notice is that as the number of `per_frame` photons increases, only the time dedicated to the shooting of the photons increases. The balancing, radiance estimate, and rendering times all remain constant. Finally, the moment in which the times for the shooting and balancing stages are equal should be noticed. This moment will be discussed further in Section 5.3.

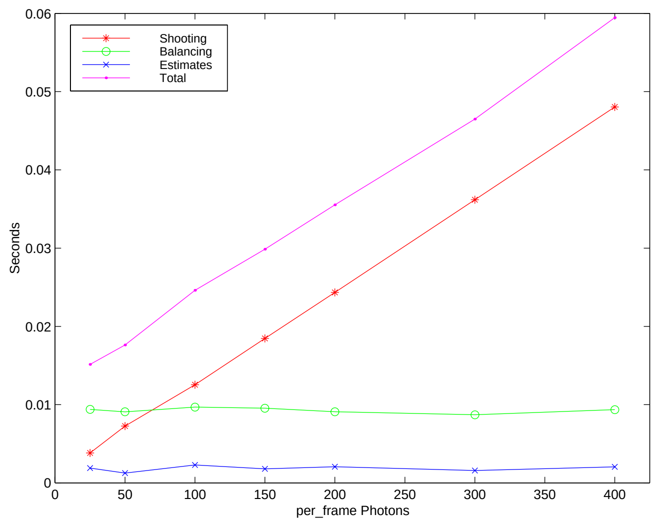


Figure 21: The per frame rendering times as `per_frame` is increased.

Figure 22 shows how changing the value for `total` effects the per frame rendering times. Each test scene consisted of 16 surfaces, 100 `per_frame` photons, a `max_level` of 3, 100 photons in each radiance estimate, and a 512 by 512 pixel output window. First of all, the per frame rendering time never exceeds beyond 0.04 seconds, which is plenty fast enough for fluid animation. Secondly, one should notice that increasing the `total` photons increases the time for both the balancing and radiance estimate stages of the rendering while all of the other stages remain constant. As the number of `total` photons is doubled, the balancing time is also doubled; however, the radiance estimate times do not. The time required for the radiance estimate times increase at a much lower rate than the balancing stage times as the `total` photons are increased. This is simply because balancing takes

$O(n \log_2(n))$ time and radiance estiamtes take $O(\log_2(n))$ time. Once again, the moment in which the times for the shooting and balancing stages are equal should be noted for discussion in Section 5.3.

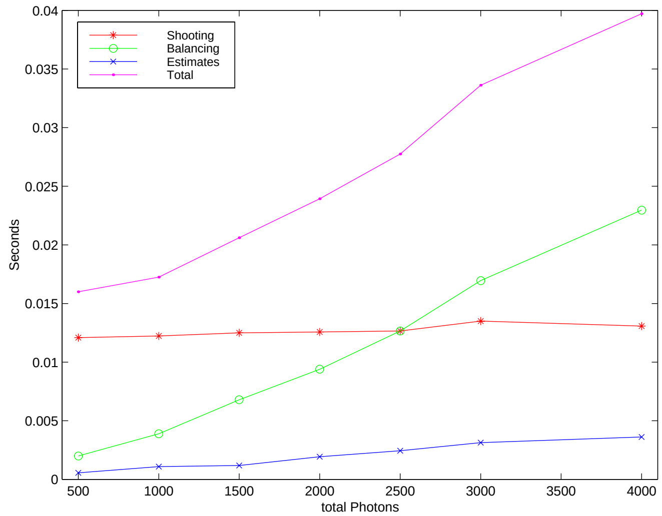


Figure 22: The per frame rendering times as `total` is increased.

Figure 23 shows how changing the value for `max_level` effects the per frame rendering times. Each test scene consisted of 16 surfaces, 100 `per_frame` photons, 2000 `total` photons, 100 photons in each radiance estimate, and a 512 pixel by 512 pixel output window. What one notices first is that every stage in process increases as `max_level` is increased. Thus, it is highly important that the value of `max_level` is kept as small as possible. Section 5.3 will show that a `max_level` of 3 is plenty for real time rendering.

What can be learned from Figures 21, 22, and 23 is that the proposed real time photon mapping algorithm can actually be performed in real time. Unfortunately, as Figure 24 shows, as the number of surfaces in the scene are increased, the per frame rendering times soon become much too slow for interactive purposes. The times quickly rise above a single second per frame, which makes real time photon mapping impractical for scenes with many surfaces. What is most important

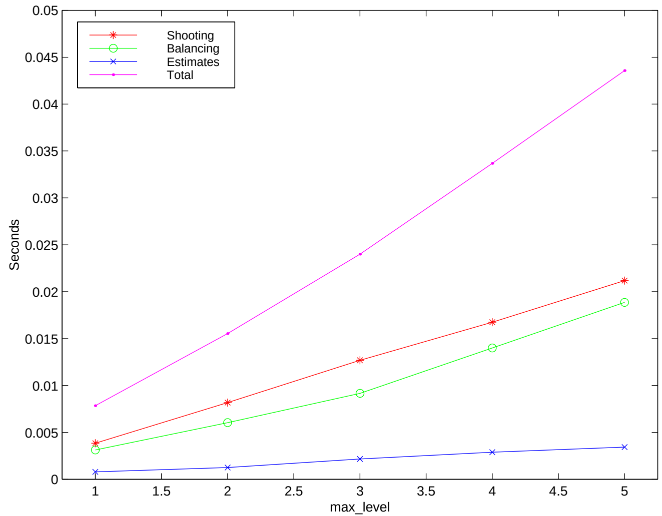


Figure 23: The per frame rendering times as `max_level` is increased.

is that only the shooting and radiance estimate stages add to the slow results. Section 5.2 will show how the inclusion of the speedups presented in Section 4.4 can be used to reduce per frame rendering times so that photon mapping can still be performed in real time.

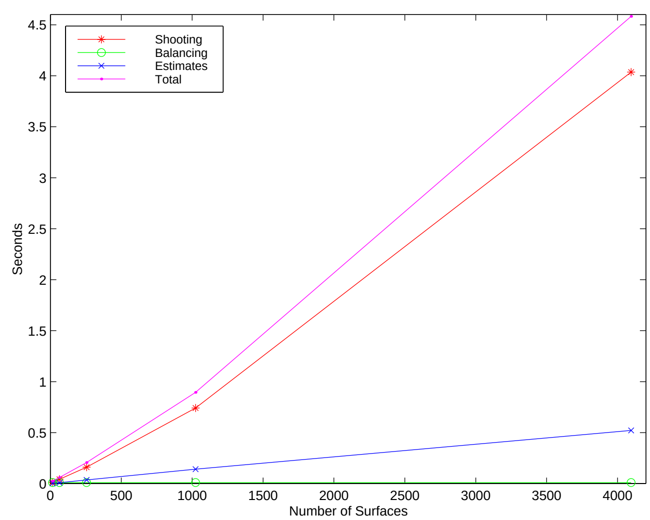


Figure 24: The per frame rendering times as the number of surfaces is increased.

5.2 Speedup Performance

The results obtained in Section 5.1 work well for a simple scene with 16 surfaces but in order to render more complex scenes in real time, some of the suggested speed improvements must be used. A comparison of the benefit of these speedups is thus quite important to the real time photon mapping algorithm.

Figure 25 shows how using scene simplification can be used to keep per frame rendering times low as surfaces are increased. In each case, the number of surfaces in the simplified scene is kept constant at 16. When compared to Figure 24, it is obvious to see that the shooting stage is no longer a speed issue. Thus, as the number of surfaces increases, as long as the number of surfaces checked stays the same, speed problems resulting from the shooting stage will not occur.

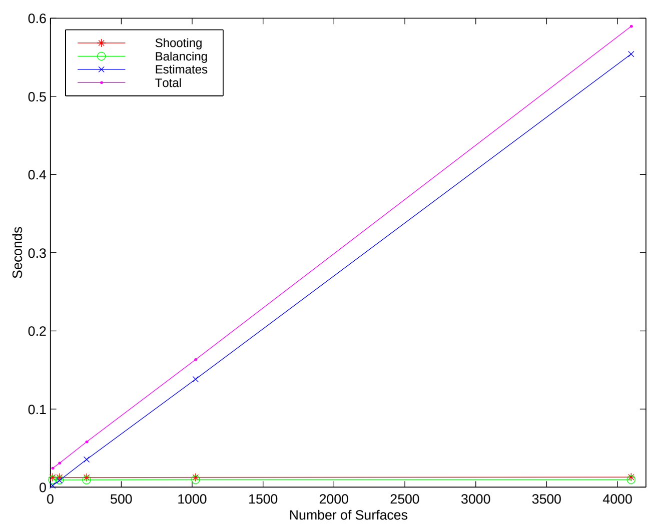


Figure 25: The per frame rendering times as the number of surfaces is increased under scene simplification.

However, Figure 25 also shows that the time required by the radiance estimates is now a major problem. This problem can be solved by using either back face culling or vertex cornering in order to reduce the times required for radiance estimates. Figure 26 shows how culling can keep some of the radiance estimates from being performed resulting in faster rendering times. Figure 27 shows how vertex corning can keep radiance estimates at the same position from being repeated. Though culling does reduce rendering times, vertex corning is shown to be a major improvement in the radiance estimate times.

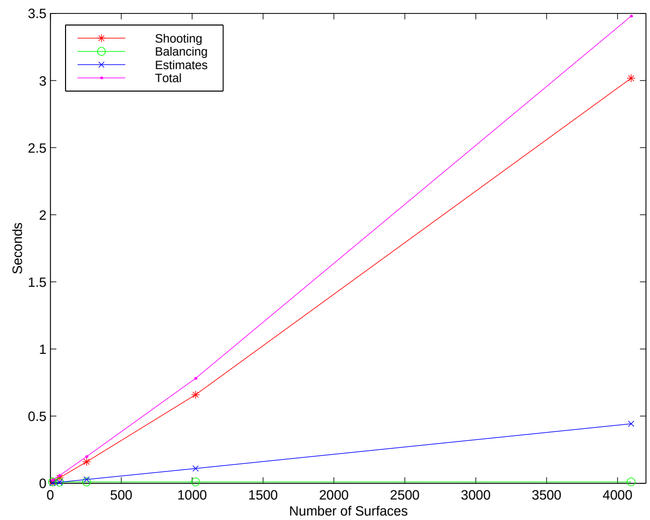


Figure 26: The per frame rendering times as the number of surfaces is increased under back face culling.

Figures 24 shows that if the number of surfaces the photons are checked with is not reduced somehow, the photon shooting and radiance estimate phases will dominate the frame rendering costs. However, Figures 25, 26, and 27 also show that with the included speedups, the per frame rendering time can remain very similar to that of Figure 21. This is an extremely important statistic because as scenes get larger, a heavily time consuming stage will most likely mean producing frames at a rate that is unacceptable to the human eye.

5.3 Visual Results

For an algorithm that is so heavily visually dependent, tests must not be performed on numbers alone. The algorithm must not only run fast enough, but must look

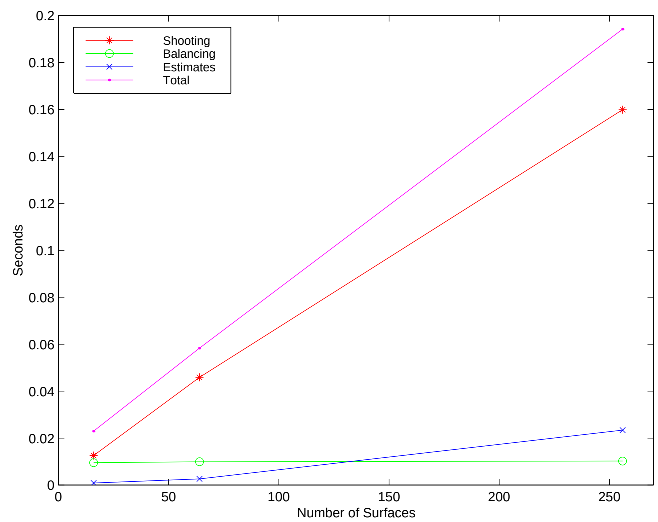


Figure 27: The per frame rendering times as the number of surfaces is increased under vertex cornering.

realistic enough as well. Several screenshots of the proposed real time photon mapping algorithm have been included in this section so that visual results can be discussed.

Figure 28 shows a few frames of output with 100 `per_frame` photons, 2000 `total` photons, a `max_level` of 3, and 256 surfaces. The scene was a simple box containing two other smaller boxes. The light source (an invisible point light source) makes a circular motion around the room demonstrating how a changing position of a light source can be handled by real time photon mapping. The glow of light can be seen to move from frame to frame, giving the correct output for simulating dynamic illumination.

Figure 29 shows the same scene but only renders the photon map, thus only the positions of the photon hits can be seen. These frames show how the photon hits change as the scene changes. The highly concentrated areas of photons show where in the scene the brightest illumination should be. When compared with Figure 28, a direct correlation between illuminated surfaces and highly concentrated areas of photons can be shown. A larger version of some of the frames of this scene has also

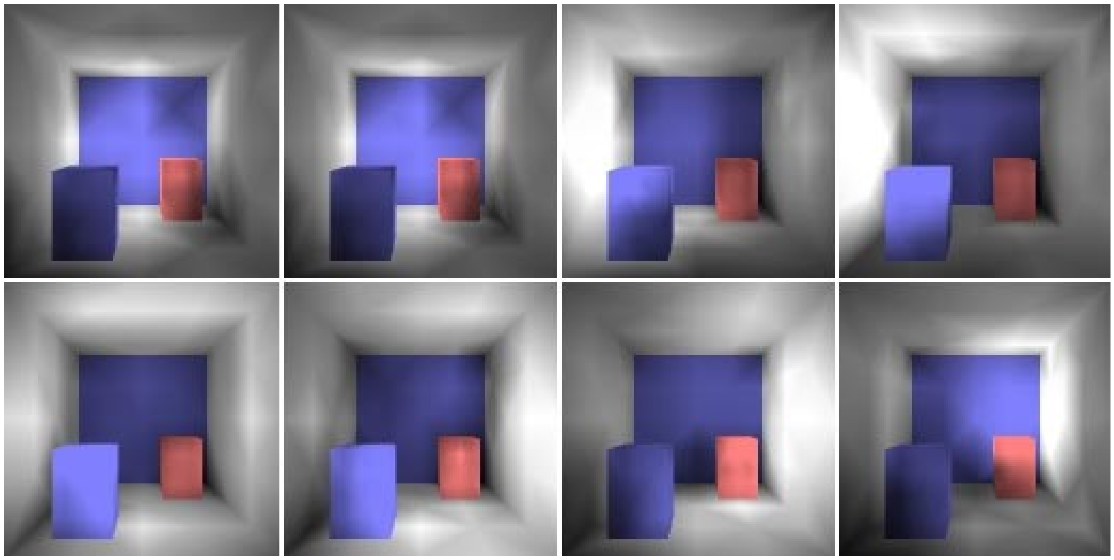


Figure 28: Eight frames of the real time photon mapping output of a point light circling around a simple box scene.

been included as Figure 30 and compared to corresponding frames from Figure 28.

There is a major distinction between images of the same scene but with a different number of surfaces. Figure 31(a) is the box scene with only the original 16 surfaces included. When compared to Figure 31(d) with those 16 surfaces uniformly subdivided into 1024 surfaces, Figure 31(a) looks much simpler and less realistic. The surfaces themselves are rendered with more precision as well by OpenGL. Although the lighting seems more blotchy, the illumination more accurately simulates reality.

There is also a major visual difference between images of the same scene but with different values for the radiance estimate. In Figure 32, (a) was rendered with 50 photons in the radiance estimate and a maximum distance of 2.0 while (b) was rendered with 150 photons and a distance of 4.0. It is obvious that the second image is a much better simulation of the illumination in the scene, and the per frame times are not effected much at all. Thus, rendering with more photons in the

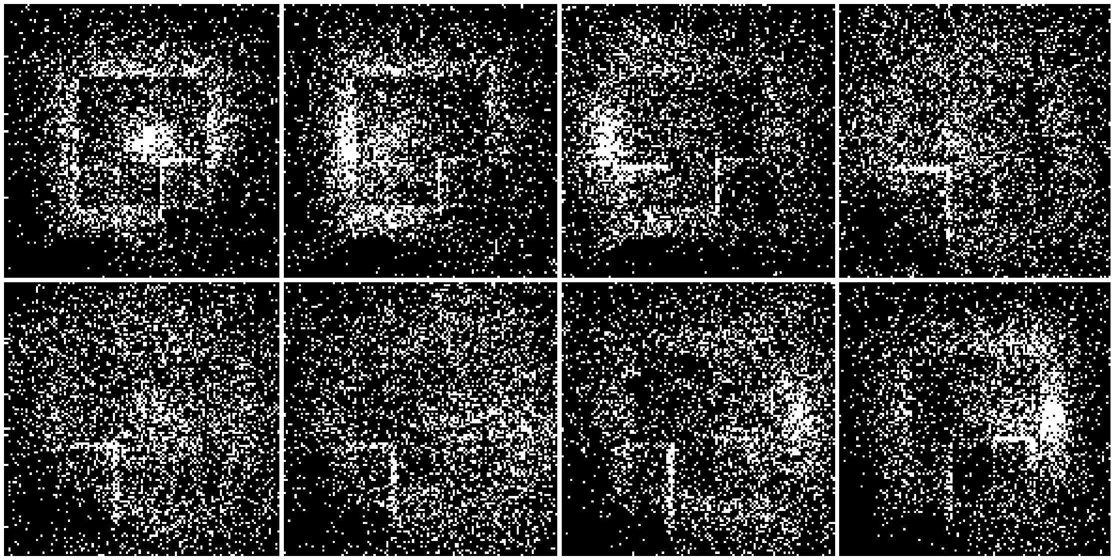


Figure 29: Eight frames of the photon hits of the simple box scene.

radiance estimate and a larger maximum distance gives more realistic, smoother results with little cost to the rendering time. However, one must remember that if the maximum distance is too large that photons will begin to be included in the radiance estimate that are not appropriate for the vertex in question.

The visual effects of changing the number of `per_frame` photons and `total` photons is slight when comparing only single frames. In order to see the difference, one must view the animation itself. What can be seen when `per_frame` is too small in comparison to `total` is that the illumination from the light source does not appear until after the light has left its position. This can be stated more concisely as the scene reacting too slowly to changes. This happens because there are too many old photons still left in the scene that continue to show the illumination in previous areas. On the other hand, if `per_frame` is too large in comparison to `total`, then the illumination fluctuates. This is because there are too many new photons being shot per frame and the random nature of the diffuse reflections changes the illumination at each vertex greatly.

With the use of the per frame rendering times from Section 5.1 and these visual

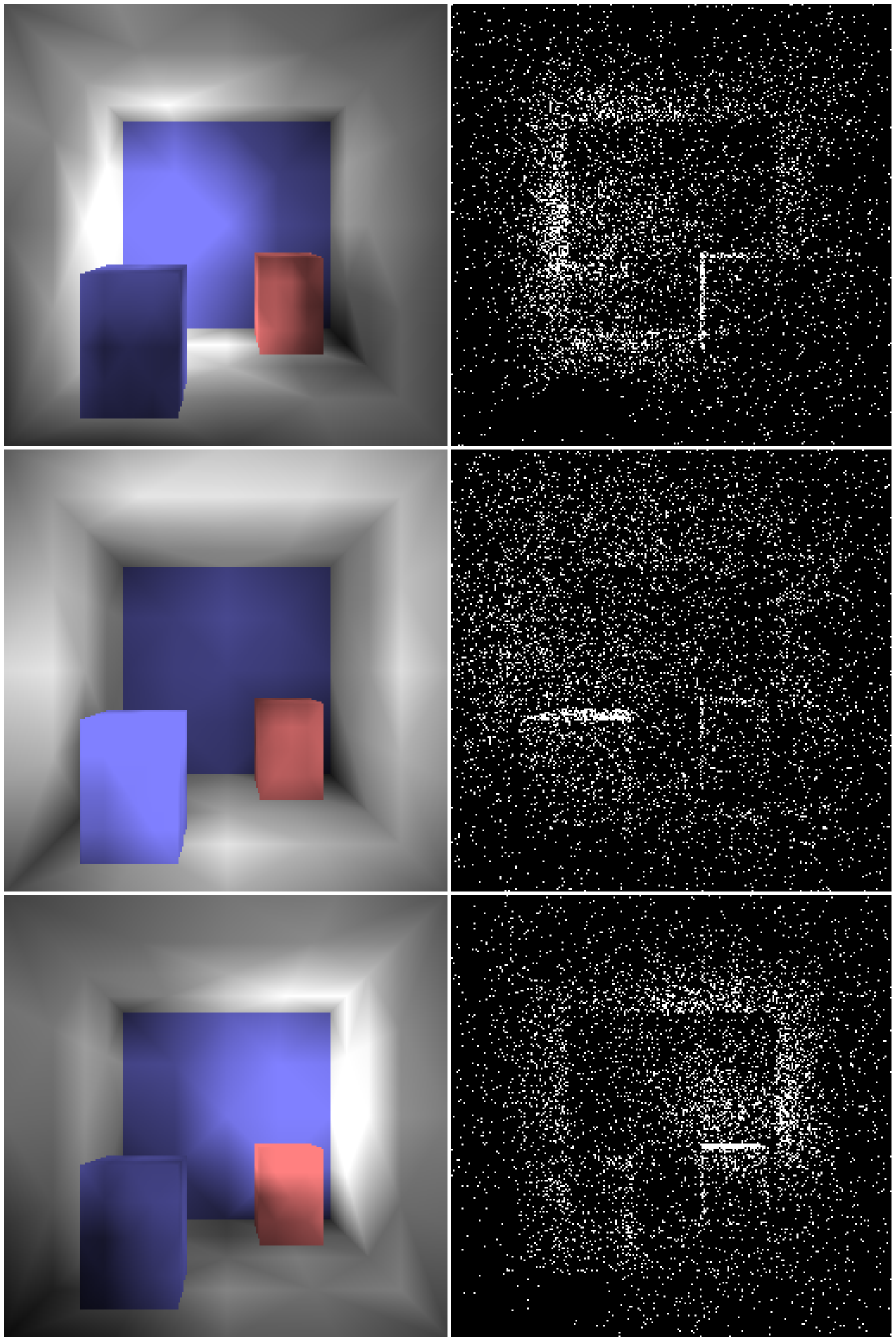
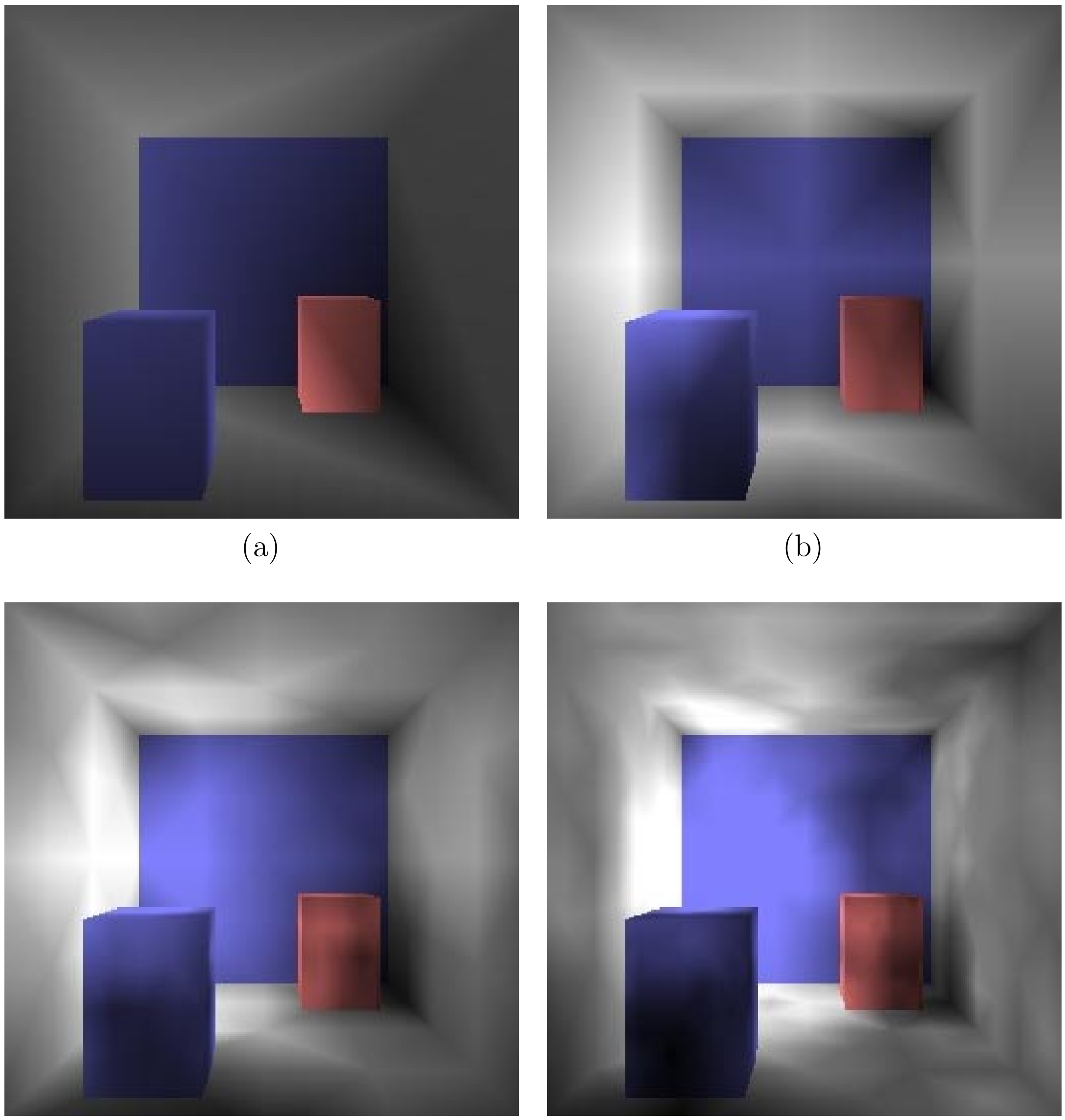
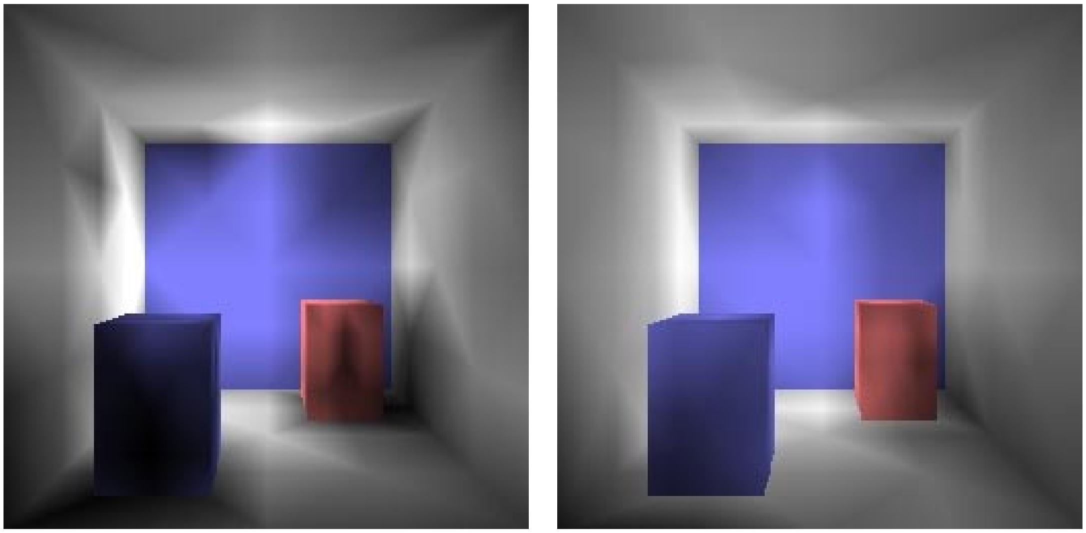


Figure 30: Three frames of the box scene comparing the rendered image and the photon hits.



(a) (b) (c) (d)

Figure 31: The box scene rendered with (a) 16 surfaces, (b) 64 surfaces, (c) 256 surfaces, (d) 1024 surfaces



(a) (b)

Figure 32: The box scene rendered with (a) 50 photons in the radiance estimate and a maximum distance of 2.0 and (b) 150 photons and a maximum distance of 4.0

results, the effects of changing `per_frame` and `total` can be discovered. Table 1 discusses these effects. Finding the values that are "appropriate" may involve several trials; however, a good "rule of thumb" is to find the values at which the shooting and balancing stages take the same amount of time. These moments can clearly be seen in Figures 21 and 22.

The use of different distributions of photons cannot easily be seen from a single frame of the rendered scene. The major changes occur when the animation itself is viewed. A random distribution of the photons can add some extra fluctuation in the form of flickering in the scene. However, a static distribution over the `total` photons reduces this fluctuation greatly. A static distribution over the `per_frame` photons reduces this more, but it does result in low coverage of the illumination. Figure 33 shows the differences between the photon hits of the random and static distributions.

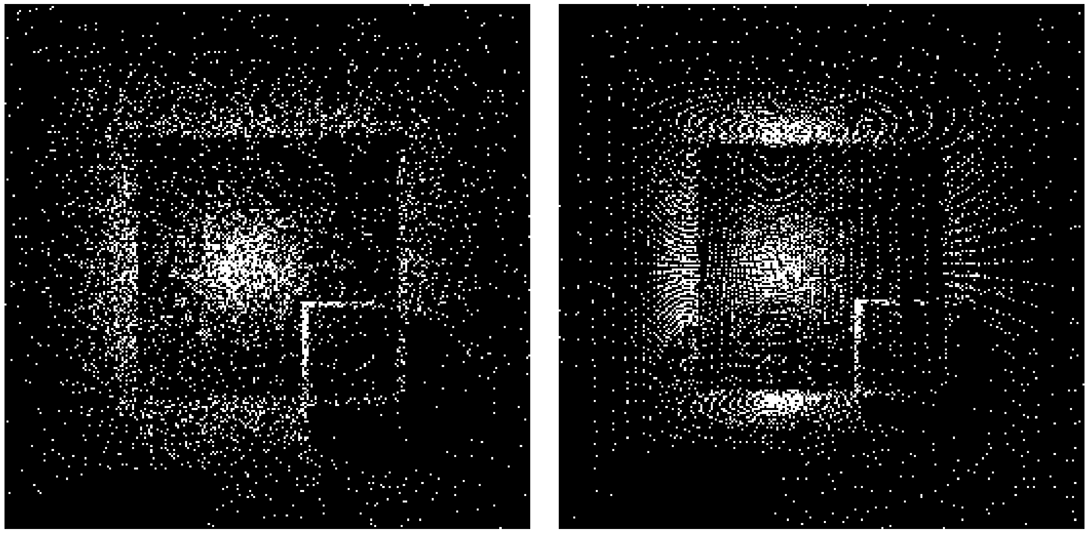
Table 1: Photon number selection guidelines

`total`	`per_frame`	*Result*
Too small	Too small	Fast, inaccurate radiance estimates.
	Too large	Illumination fluctuation. Slow shooting time.
	Appropriate	Fast results. Slight illumination fluctuation.
Too large	Too small	Scene reacts slowly to changes. Slow balancing times.
	Too large	Very slow processing times.
	Appropriate	Scene reacts slowly to changes. Slow balancing times.
Appropriate	Too small	Inaccurate radiance estimates.
	Too large	Slight illumination fluctuation. Slow shooting times.
	Appropriate	Great results, good processing time.

5.4 Shadows and Color Bleeding

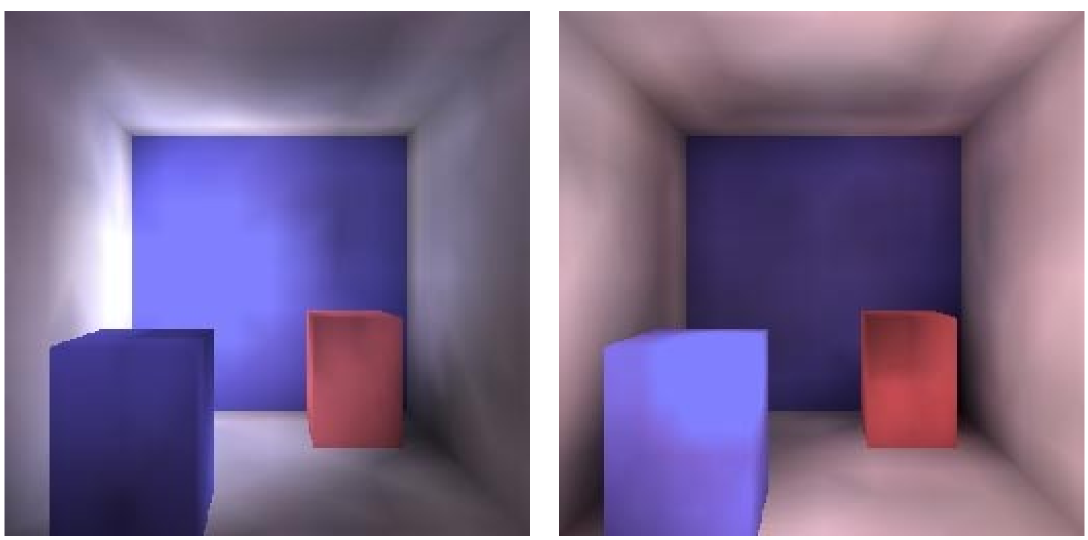
Besides allowing for diffuse reflections, real time photon mapping can be used to add shadows to the scene. Each of the screenshots in Section 5.3 illustrates this. This is achieved by storing every photon hit in the photon map so that direct illumination is included as well. This will increase the number of photons needed in the photon map, but the `max_level` of 3 can still be maintained. One direct illumination level, and two indirect illumination levels are plenty for real time rendering.

Another phenomenon that can now be performed in real time is color bleeding. By using the same methods of simulating color bleeding in the original photon mapping algorithm, it can be implemented in the real time version. Figure 34 shows the box scene rendered with color bleeding. A large difference can be seen when the light is closest to the blue wall in the back of the room and when the light is closest to the red wall behind the camera.



(a) (b)

Figure 33: The differences between (a) random and (b) static photon shooting distributions.



(a) (b)

Figure 34: Color Bleeding of (a) a blue wall and (b) a red wall in real time photon mapping.

6 Conclusion

Interactive rendering has for a long time been limited to local illumination and only recently has seen an inclusion of estimations of global illumination. Real time ray tracing and radiosity techniques have been introduced, but can only lead to frustrating shortcomings inherent in each algorithm. There are additions to both ray tracing and radiosity that can be used to correct these shortcomings, but they take extremely long amounts of time for a single image, let alone an interactive setting. However, by using the concepts in photon mapping to create a real time global illumination system, interactive graphics programming can be taken to a new level of realism that includes diffuse reflections, shadows, and color bleeding. And, as processing power increases, instead of simply catching up with the speed required for real time ray tracing and radiosity, real time photon mapping can be well on its way to practical and everyday use.

In this thesis we have modified the original photon mapping algorithm, an algorithm for rendering extremely realistic images, and adapted it to run in an interactive environment. We have demonstrated that, for the examples shown, it is possible to render a photon mapped scene with 256 surfaces at a rate of 40 frames per second. These results are due to the implicit speed of the photon mapping algorithm and several improvements described in this thesis.

Many additional features can be added to improve the proposed algorithm; however, there are a few topics that we believe are of the upmost importance to the practicality and realism of real time photon mapping.

Balancing the K-D Tree: The time required to balance the k-d tree takes far too long in comparison to how little work it is doing. The fact that only a fraction of the photons are being rebalanced is incentive enough to find a way to balance the k-d tree faster by using knowledge of other structures.

Perhaps an inserting, deleting, or merging function can be used to speed up the balancing process. There may even be a way to remove the k-d tree entirely, removing the balancing stage altogether.

Specular Surfaces: Another topic for future work is combining some of the work on real time ray tracing with real time photon mapping so that specular surfaces can be rendered as beautifully as ray tracing renders them but in real time. Achieving this would certainly add another level of realism to interactive rendering.

Caustics: It seems reasonable that caustics could be implemented by extending this research. Proving that such phenomenon can be rendered in real time would also add another level of realism.

Surface Subdivision: A method that may prove to be useful for subdividing the surfaces in a scene would be to find areas of highly concentrated photons during the balancing process, these areas could then be reduced to a single vertex each and incorporated into the scene. This could be a method of finding caustic locations as well.

Fluctuations: The visual results of the proposed real time photon mapping algorithm show some undesired fluctuation that cannot be corrected by simply adjusting the `total` and `per_frame` photons. A way of reducing this fluctuation would be another worthwhile research topic.

A List of Variables

Variable	*Type*	*Description*	1^{st} *Reference*
ξ_1	double	Random variable	Section 3.2
ξ_2	double	Random variable	Section 3.2
θ	double	Spherical angle	Section 3.1
ϕ	double	Spherical angle	Section 3.1
C	RGB color	The color given to a pixel.	Section 2.1
$\vec{d}$	Vector	The incident direction.	Section 2.1
`dir`	Vector	A direction vector.	Figure 16
`hit_point`	Vector	The position on a surface that a photon has hit.	Figure 17
`i`	int	A loop variable.	Section 9
`index`	int	The currently chosen index of an array.	Figure 9
L	RGB color	The color of a light.	Section 2.1
$\vec{l}$	Vector	The position of a light source.	Section 2.1
`level`	int	The number of reflections a photon has gone through.	Figure 15
`light_power`	Vector	The color and intensity of an emitted photon.	Figure 15
`loc`	int	The current location in the `photon_location[ ]` array.	Figure 18
m_1	double	Index of refraction.	Section 2.1
m_2	double	Index of refraction.	Section 2.1
`max_level`	int	The maximum times a photon can be reflected or transmitted.	Section 4.1.2
$\vec{n}$	Vector	The surface normal of a surface.	Section 2.1
`node`	Photon	A single photon to store.	Figure 17
`num_photons`	int	The current number of photons to iterate through.	Figure 15
`per_frame`	int	The number of photons to shoot each frame.	Section 4.1.1

Variable	*Type*	*Description*	1^{st} *Reference*
`phi`	float	Spherical angle	Figure 13
`Photon`	Photon	The data structure of a photon.	Figure 13
`photon_location[ ]`	int array	The position of each photon in the `photons[ ]` array.	Section 4.1.2
`photon_ray`	Ray	A ray denoting the position and direction of a photon.	Figure 15
`photons[ ]`	Photon array	The array for the k-d tree that stores all of the photon hits.	Section 4.1.2
`plane`	int	The plane in the k-d tree to search by.	Figure 13
`pos`	Vector	A position vector.	Figure 17
`power`	Vector	The current color and intensity of an emitted photon.	Figure 16
$\vec{r}$	Vector	The reflected direction.	Section 2.1
`r_ray`	Ray	The reflected ray.	Figure 16
S	RGB color	The color of a surface.	Section 2.1
$\vec{s}$	Vector	A position on a surface.	Section 2.1
`scale`	float	The scaling factor to scale a photon's power by.	Figure 18
$\vec{t}$	Vector	The transmitted direction.	Section 2.1
`theta`	float	Spherical angle	Figure 13
`total`	int	The total number of photons to be shot into a scene.	Section 4.1.1
`used`	bool	Flag representing if a photon is currently "live" in the scene.	Section 4.2

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